The incompatibilities between the standard theory of interstellar extinction and observations.

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In this paper I review a series of observations which do not agree with the standard interpretation of the extinction curve. The consequence is that light we receive from a reddened star must be contaminated by starlight scattered at very small angular distances from the star. The true extinction curve is a straight line from the near infrared to the far-UV. If so, all interstellar grains models must be questionned. Another conclusion concerns the average properties of interstellar grains which seem much more uniform than previously thought.

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1 Introduction

Although interstellar dust represents a very small part of interstellar matter, it is responsible for the extinction of starlight, it accounts for a large part of the scattered starlight we receive from nebulae, and it is also responsible for the thermal emission of interstellar clouds in the infrared. Thus, interstellar dust plays a most important role as a tracer of the distribution and of the structure of interstellar matter. It is also involved in the chemistry of the interstellar medium.

The study of interstellar dust has led to several dust models that are heavily constrained by the average extinction curve obtained from observations of stars through interstellar clouds. It is of primary importance to have a correct interpretation of the extinction curve to fully understand the interstellar medium.

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The standard interpretation of the extinction curve separates the light spectrum into three parts: the visible, the 2000Å bump, and the far-UV region. Separate types of particles (grains or molecules) with specific size distributions and extinction properties are assumed to be responsible for the extinction of light in each of these wavelength domains. The variation of the extinction curve with the line of sight is interpreted as the effect of different proportions of each type of particles from cloud to cloud. All current dust models are based on this paradigm.

In a preceding series of papers (Zagury, 2000a,b, 2001a,b, 2002) I have detailed observations which contradict these models, question the standard interpretation of the extinction curve and call for another explanation. There are important consequences involved, as we need to reconsider the nature of light received from a reddened star. Which, in turn, will deeply affect the analysis and the interpretation of the observations on interstellar matter. The applications are numerous ranging from practical aspects (correcting the reddening for stellar distance estimations), to more theoretical problems on the nature of interstellar dust, its properties depending on environment, etc...

In this paper I first reviewed the principles of the standard interpretation of the extinction curve (section 2). The observations which run contradictivelly this interpretation are summarised in section 3. The implications and ways to reconcile theory and observation are discussed in section 4.

2 The extinction curve and its' standard interpretation

The light we receive from a reddened star is extinguished by a factor $e^{-\tau_\lambda}$, where τ_λ is the extinction optical depth, at wavelength λ, of the interstellar matter between the star and us. If F_λ and $F_{0\lambda}$ are the flux we receive from the star and the one we would receive if the star was not reddened:

$$F_\lambda = F_{0\lambda} e^{-\tau_\lambda} \tag{1}$$

In magnitudes:

$$m_\lambda = m_{0\lambda} + 1.07\tau_\lambda = m_{0\lambda} + A_\lambda \tag{2}$$

Since $F_{0\lambda}$ or $m_{0\lambda}$ are not known, they are replaced by the values observed for a non-reddened star of same spectral type. The extinction curve A_λ is then obtained, to within an additive constant generally determined from the V-magnitudes of the stars. The extinction curve can be normalized by $E(B-V) = A_B - A_V$, proportional to the slope of the extinction curve in the visible.

Seaton (1979) gave the average normalized extinction curve for the stars of the solar neighborhood. The standard theory separates this curve into three parts: the visible, the 2200Å bump region, and the far-UV. The normalised extinction curve in the direction of a reddened star follows Seaton's curve in the visible, but large variations are observed in the UV, especially in the far-UV (Bless & Savage, 1972). The standard theory attributes these variations to the combined effect of the extinction of starlight by three types of particles, which are present, but in variable proportions, in the interstellar clouds. The linear in $1/\lambda$ visible extinction is due to a distribution of large grains, which have a flat scattering cross section in the UV (figure 1 in this paper or figure 2 in Greenberg (2000)). The bump region is attributed to very small grains (VSG). Last, the far-UV rise of the extinction curve should be due to molecules, thought to be poly-aromatic (the PAH). 'Large' or 'small' particles refer to the wavelength domain which is considered, since the ratio of the size of the particle to the wavelength is the fundamental parameter in scattering theory.

By allowing the proportion of each type of particles to vary from cloud to cloud the standard theory acquires three degrees of freedom which permits to fit most extinction curves. But, there does not seem to be any logic behind the grain type repartition with environment (density, exposure to UV radiation. . .) (Jenniskens & Greenberg, 1993).

This freedom is paid with an important compensation. The particular extinction curve each type of grains must have, the necessity to respect cosmic abundances, tightly constrain the nature of the grains and led to several models of grains. To date, none of the models of interstellar dust in use (the first PAH model of Désert et al. (1990), the unified model of Li & Greenberg (1997), the model of Mathis (1996)) are truly satisfying.

3 The standard theory against observations

The standard theory can be tested in several ways. I have proposed four tests, three of which are detailed in the following sub-sections.

3.1 The UV spectrum of nebulae

The UV spectrum of a nebula illuminated by a nearby star is well reproduced by the product of the spectrum of the source star and of a linear function of $1/\lambda$ (Zagury, 2000a).

Neither the large grains supposed to be responsible for visible extinction -of which the far UV extinction cross section is nearly independent of wavelength-, nor the small particles supposed to be responsible for the UV extinction -which should scatter starlight as $1/\lambda^4$- can explain this relation between the nebula and the star spectra.

The linearity in $1/\lambda$ of the nebula to the star spectrum ratio suggests that the scattering law valid in the visible extends to the UV.

We also do not observe any excess of scattering in the bump region (Zagury, 2000a), which means that if there is a specific extinction at 2200 Å, it is absorption only. But, some nebulae, associated to low-reddened stars, do not show a bump. Therefore, either the small grains which, according to the standard theory, are responsible for the bump are not present (or only in very small quantities) in low column density clouds, or the bump is not a common absorption process.

3.2 The extinction curve in directions of very low reddening

The spectra of stars of same spectral type and very low reddening, not reddened enough to have a 2200Å bump, differ one from the other by the same exponential of $1/\lambda$ in the visible and in the UV (Zagury, 2001b). Thus, the extinction law in very low column density media is the same in the visible and in the UV, which confirms what is already suggested by the UV observation of the nebulae.

3.3 The extinction curve in directions of low reddening

Increasing the reddening of the stars, the extinction law deviates from the $1/\lambda$ linear extinction in the far-UV first, whereas the linear visible extinction law still extends to the bump region (Zagury, 2000b). The reduced spectrum of the stars is an exponential in the near-UV. This exponential prolongs in the UV the visible extinction of the stars' light. The deviation from the visible extinction of the far-UV reduced spectrum clearly appears as an additional component superimposed on the tail of the exponential (figure 2).

Here again, the standard theory can not explain in a natural way the extension of the visible extinction law to the near-UV.

4 Discussion

The observations mentionned in section 3 contradict the standard theory of interstellar extinction.

The only alternative to the standard theory was first mentionned by Savage (1975). It implies that when a reddened star is observed in the UV a non negligible proportion of scattered light is re-introduced into the beam of the observation.

Snow & York (1975) have rejected this hypothesis from UV observations of σ-Sco with two different apertures of $8' \times 3^\circ$ and $0.3'' \times 39''$. There is no difference between the UV spectra of the star observed with one aperture or the other. However, these observations only prove that if scattered starlight contaminates the spectrum of reddened stars, it must be within an angle of $0.3''$ from the star.

The observations of section 3 are explained if a non-negligible contribution of scattered light is added to the observed direct starlight. When there is little interstellar matter between the star and the observer the contribution of scattered light is negligible: we observe the direct starlight only, slightly extinguished, and the observed extinction reflects the exact extinction law of starlight by interstellar dust. If the column density is increased, scattered light first appears in the far-UV, because extinction, hence the number of photons available for scattering, increases towards the shortest wavelengths. Still increasing the reddening, the scattered starlight will merge in the visible, provoking the departure of Seaton's curve from the linear extinction between $1/\lambda \sim 2.5\mu\mathrm{m}^{-1}$ and $1/\lambda \sim 4\mu\mathrm{m}^{-1}$ (figure 1).

There are many consequences. Firstly, the extinction curve is a straight line from the near infrared to the far-UV. Secondly, there is a priori non reason to suppose changes of the average properties of interstellar dust from one interstellar cloud to another: the law of starlight scattering found for the nebulae for instance is the same in the different nebulae. If, in the near future, spectral observations of nebulae confirm that this law extends to the visible, we will also be able to conclude that the albedo and phase function of interstellar grains are wavelength-independent from the near infrared to the far-UV. Variations of the $R_V = A_V/E(B-V)$ parameter are observed for some stars and used as a proof of variations of the properties of interstellar dust. These variations will as well be exlained by the slight modification, due to the scattered starlight, of the slope, $2E(B-V)$, of the visible extinction curve of the stars (Zagury, 2001a).

It also follows that current models of interstellar dust, formed on an overly direct interpretation of the particularities of the extinction curve, are questionnable.

There are two practical aspects of this research which merit mentionning. The papers I have published in the two preceding years show the need of acquiring stellar spectra on an as large as possible wavelength range. The simultaneous study of visible and UV extinctions becomes necessary to understand and to separate the different contributions of direct and scattered starlights. This necessity of separating direct and scattered starlight implies that the current method of using the magnitudes of the spectra rather than the spectra themselves is not recommended. The traditional way would be best if there was direct starlight only, but the separation of two additive components is much easier from the raw spectra than from their logarithm.

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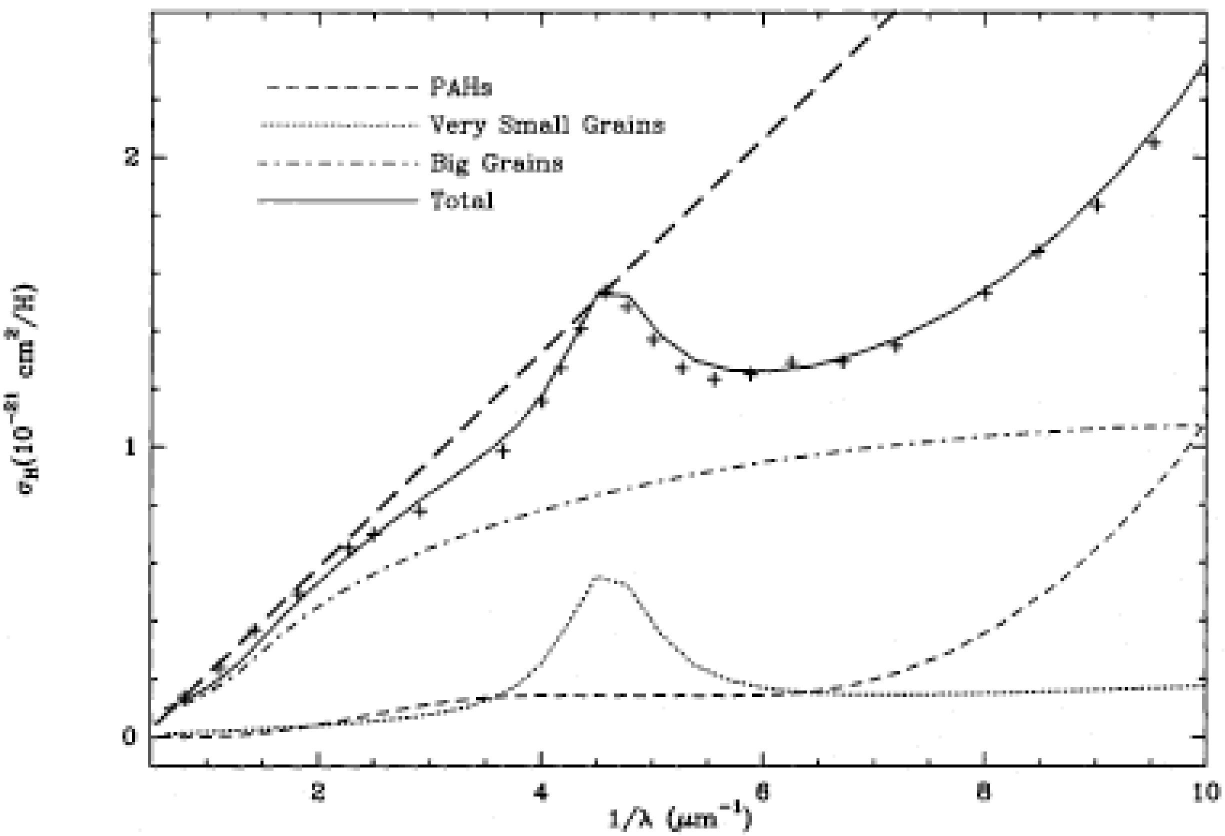

Fig. 1. Seaton's extinction curve (plain line) and the separate extinction curves of the large grains, the very small grains (VSG), and the poly-aromatic molecules (PAH). From Désert et al. (1990). I have added (dashes) the linear extinction curve.

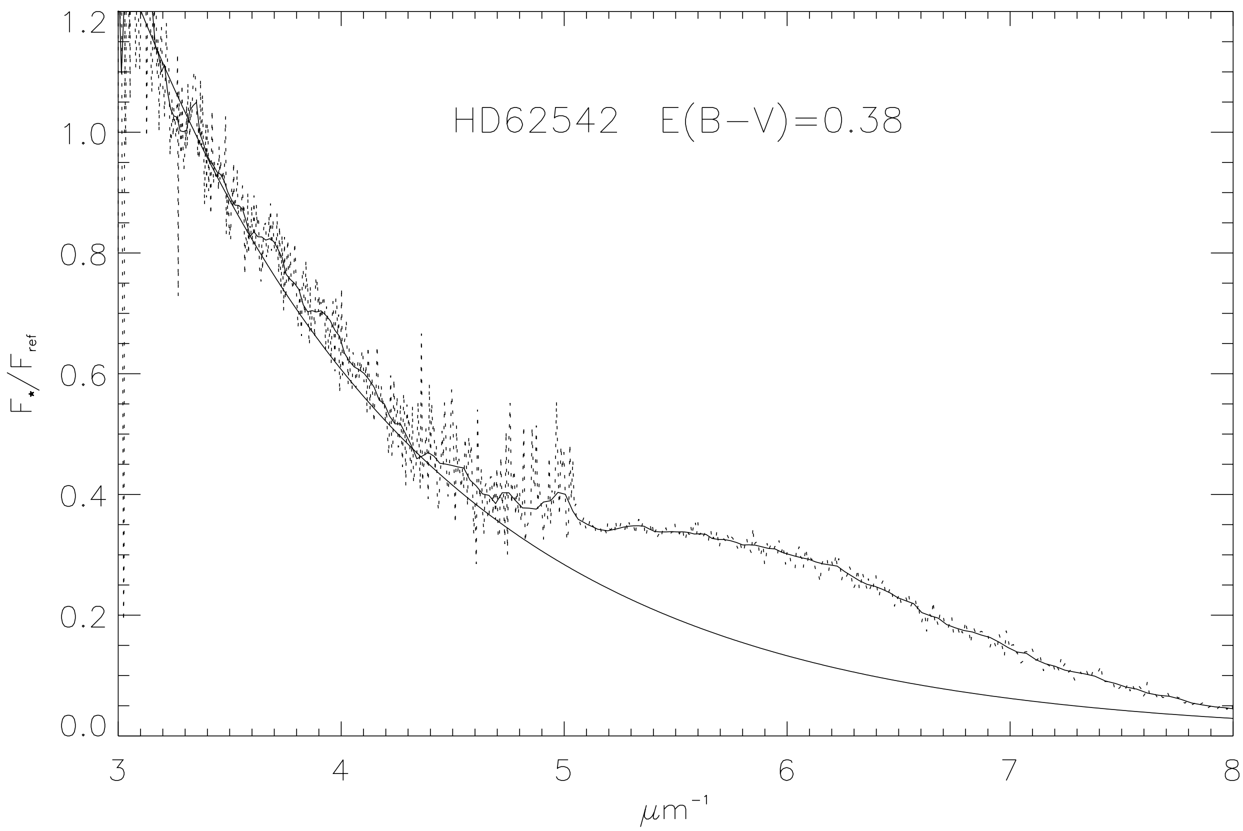

Fig. 2. The spectrum of HD62542 divided by the spectrum of the non-reddened reference star HD32630. The visible extinction corresponds to the exponential and extends to the bump region. The far-UV difference between the two curves clearly appears as an excess of light superimposed on the tail of the exponential. This excess is attributed to an additional component of scattered light.